To pdf - TIAM-UCL

From IAMC-Documentation

Reference card - TIAM-UCL

Contents

The reference card is a clearly defined description of model features. The numerous options have been organized into a limited amount of default and model specific (non default) options. In addition some features are described by a short clarifying text.

Legend:

- ☐ not implemented
- ☑ **implemented**
- ☑ **implemented (not default option)**

About

Name and version	TIAM-UCL
Institution and users	University College London (UCL), UK, https://www.bartlett.ucl.ac.uk/energy. main users: Energy modellers
Documentation	TIAM-UCL documentation consists of a referencecard and detailed model documentation

Model scope and methods

Model documentation: Model scope and methods - TIAM-UCL

Objective TIAM-UCL (TIMES Integrated Assessment Model) uses the TIMES modelling platform, which is a successor of the MARKAL platform. The markal/times modelling concept was originally intended to analyse energy systems at a regional or global level and has evolved to also describe greenhouse gas emissions. Scenario based simulations maximize the total discounted sum of consumer and supplier surplus over the model horizon, while taking into account the constraints (e.g. energy demand to be fulfilled, availability of energy resources etc).

Concept Energy Systems partial equilibrium

Solution method Linear optimisation

Anticipation Perfect Foresight (Stochastic and myopic runs are also possible)

Temporal dimension Base year:2005, time steps:5 years up to 2070 and 10 years beyond, horizon: 95 years (2005-2100)

Note: Year divided to six time slices + an additional peaking constraint.

Spatial dimension Number of regions:16

1. Africa
2. Australia
3. Canada
4. Central and South America
5. China
6. Eastern Europe
7. Former Soviet Union
8. India
9. Japan
10. Mexico
11. Middle East
12. Other Developing Asia
13. South Korea
14. United Kingdom
15. United States of Amercia
16. Western Europe

Note: UK split as separate region compared to the ETSAP-TIAM model

Policy implementation Policies can be implemented in a number of ways, depending on the type of policy. A number of general or specific policy choices can be modelled including: Emissions taxes, permit trading, specific technology subsidies, technology and/or resource constraints.

Socio economic drivers

Model documentation: Socio-economic drivers - TIAM-UCL

Exogenous drivers

- ☑ **Exogenous GDP**
- ☐ Total Factor Productivity
- ☐ Labour Productivity
- ☐ Capital Technical progress
- ☑ **Energy Technical progress**
- ☐ Materials Technical progress
- ☑ **GDP per capita**
- ☑ **Population**

☑ **GDP per household**

Note: Sectoral trajectories for Agriculture, Services and Industrial outputs

Endogenous drivers

☑ **Learning by doing**

Note: Is available but rarely used due to computational issues

Development

☑ **GDP per capita**
☐ Income distribution in a region
☐ Urbanisation rate
☐ Education level
☐ Labour participation rate

Macro economy

Model documentation: Macro-economy - TIAM-UCL

Economic sectors

☑ **Agriculture**
☑ **Energy**
☑ **Industry**
☑ **Services**
☑ **Transport**

Note: Link with MACRO Stand-Alone (module which represents all other economic sectors) available to represent rest of the economy

Cost measures

☑ **GDP loss**
☑ **Welfare loss**
☐ Consumption loss
☑ **Area under MAC**
☑ **Energy system costs**

Trade

☑ **Coal**
☑ **Oil**
☑ **Gas**
☑ **Uranium**
☐ Electricity
☑ **Bioenergy crops**
☐ Food crops
☐ Capital
☐ Emissions permits
☑ **Non-energy goods**
☑ **Diesel**
☑ **LNG**
☑ **Gasoline**
☑ **Heavy fuel oil**
☑ **Natural gas liquids**
☑ **Naphtha**

Energy

Model documentation: Energy - TIAM-UCL

Behaviour

Elastic demand mode available (includes exogenous elasticity of each energy demand with respect to their own price) Technology and region specific hurdle rates.

Resource use

☑ **Coal**
☑ **Oil**
☑ **Gas**
☑ **Uranium**

☑ **Biomass**

Electricity technologies	☑ **Coal** ☑ **Gas** ☑ **Oil** ☑ **Nuclear** ☑ **Biomass** ☑ **Wind**	☑ **Solar PV** ☑ **CCS** ☑ **Geothermal** ☑ **Hydropower** ☑ **Solar CSP**
Conversion technologies	☑ **CHP** ☑ **Heat pumps** ☑ **Hydrogen**	☑ **Fuel to gas** ☑ **Fuel to liquid**

Note: A range of sequestration and storage technologies represented

Grid and infrastructure	☐ Electricity ☐ Gas ☐ Heat	☐ CO2 ☐ H2

Note: No explicit modelling of grids, only a transmission cost and division to centralised/decentralised electricity generation technologies

Energy technology substitution	☑ **Discrete technology choices** ☑ **Expansion and decline constraints**	☑ **System integration constraints**
Energy service sectors	☑ **Transportation** ☑ **Industry**	☑ **Residential and commercial** ☑ **Agriculture**

Note: Residential and commercial are represented separately

Land-use

Model documentation: Land-use - TIAM-UCL; Non-climate sustainability dimension - TIAM-UCL

Land-use *Note: Land is not explicitly modelled.*

Other resources

Model documentation: Non-climate sustainability dimension - TIAM-UCL

Other resources	☐ Water ☐ Metals	☐ Cement

Note: Ongoing research on water and metals but not yet included in the model

Emissions and climate

Model documentation: Emissions - TIAM-UCL; Climate - TIAM-UCL

Green house gasses	☑ **CO2** ☑ **CH4** ☑ **N2O**	☐ HFCs ☐ CFCs ☐ SF6
Pollutants	☐ NOx ☐ SOx ☐ BC	☐ OC ☐ Ozone
Climate indicators	☑ **CO2e concentration (ppm)** ☑ **Radiative Forcing (W/m^2)**	☑ **Temperature change (°C)** ☑ **Climate damages $ or equivalent**

Note: Climate damages available although not often modelled CO2 is from both energy and also land-use (and forestry) included in climate module. The non-CO2 forcing agents that are not explicitly tracked are represented in the climate module by an exogenously given additional forcing factor.

Model Documentation - TIAM-UCL

TIAM-UCL is a global energy systems model that is usually run along with a climate module (calibrated to MAGICC) and an aggregated economic module (Macro Stand-Alone) in order to assess long-term energy decarbonisation scenarios and pathways.

The model is called the TIMES Integrated Assessment Model in UCL. TIMES is itself an acronym for 'The Integrated MARKAL-EFOM System'.

The framework is akin to that of a long-term social planner with perfect foresight that acheives exogenous energy demands at lowest cost given detailed energy technology assumptions and specified constraints

1) Model scope and methods - TIAM-UCL

TIAM-UCL is a bottom-up, technology-rich cost optimisation integrated assessment model created to assess the energy system costs of global decarbonisation pathways in terms of the global temperature change and/or carbon budgets.

1.1) Model concept, solver and details - TIAM-UCL

The main building blocks of TIAM-UCL is a TIMES model which includes processes and commodities, which are connected by commodity flows in a network representation called a Reference Energy System (RES). The model dynamics are determined by the time horizon and resolution, the evolutionary development of supply and technologies, the growth of the demand for energy services, and policies (e.g., mitigation targets, renewable portfolio standards), complimented by various alternate scenarios.

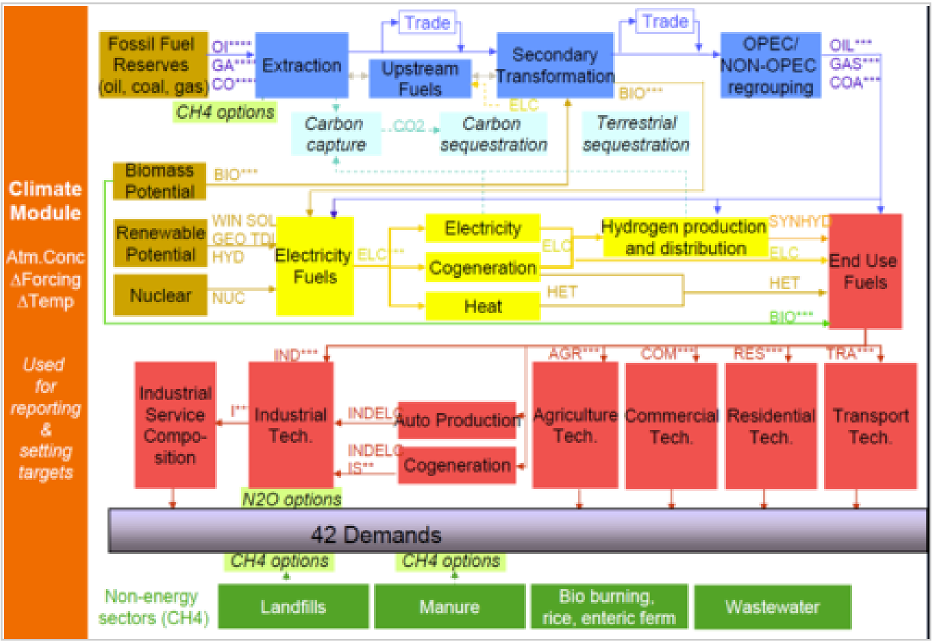


Figure 1: Figure 1.1: Simplified Reference Energy System in TIAM Source: Loulou and Labriet (2007)

In each region, the TIAM-UCL model describes the entire energy system by all essential current and future energy technologies from the primary energy supply over the processing, conversion, transport, distribution of energy carriers to the end-use sectors and the useful energy demands. These demands are linked to exogenous underlying drivers, like population growth or GDP development, via demand elasticities. Each region can trade one or more resources (fossil fuels and biomass) with other regions. Regional trade will depend on demand, supply (resource availability) and cost (resource and transportation cost) of the resources.

Base-year energy-service demands are exogenous and projected over 2005-2100 using drivers such as GDP, population, household, sector output etc. The base year (2005) final energy consumption is calibrated in the Base-Year templates module. Separate BY templates are available for each region for all end-use sectors, upstream, and the electricity generation sector. A representation of all existing technologies and resources are included in the Base-Year templates to determine the state of teh energy system in the intial period. Technologies available for the future years are modelled in a separate module called 'New Technologies'. Any region can access the technology module if it is cost effective to do so. Resource data such as cost, cumulative and annual availability of different resources are modelled in the 'Resource Module'. The world regions are linked through the trade of energy goods and CO2 via the trade module. There are separate modules available for hydrogen production, carbon sequestration, land-use CO_2 emissions, N_2O measures, CH_4 measures, etc. Climate module calculates impacts of GHG emissions in the Atmosphere (CO_2 concentration and temperature changes). Beside these modules, there are several scenario files which are used to apply different policies and constraints.

Further details on the TIAM model structure is available in Loulou and Labriet (2007).

The underlying data for the base year calibration in TIAM-UCL is the IEA Extended Energy Balances of OECD and non-OECD countries.

Software

TIAM is a whole energy system model covering from energy resources to conversion to infrastructure to end-use sectors.This is a linear programming model that minimises total discounted energy system cost in the standard version and maximises societal welfare (total surplus) in the elastic demand version to compute a partial equilibrium. Linear programming is formulated in the GAMS (General Algebraic Modelling System) language and solved via powerful linear programming optimisers (CPLEX, XPRESS).

VEDA Front-End (VEDA_FE) is one of the two interfaces available for the TIMES model. It is used to formulate the TIAM-UCL model database that lay down the basic structure of the model and hold fundamental data and assumptions for processes (technologies) and commodities. VEDA is a set of tools geared to facilitate the creation, maintenance, browsing, and modification of the large data bases required by complex mathematical and economic models. Data and assumptions are fed into VEDA_FE that provides input to the TIMES code. VEDA_FE accepts input from a variety of Excel files with different (flexible) structures that are tailored to work efficiently with data intensive models. The model is sent from VEDA_FE to GAMS where it is run. The results are then loaded into another interface, VEDA Back-End (VEDA_BE), where they can be manipulated and interpreted as necessary.

Modelling to Generate Alternatives

A critical challenge when working with global energy-environment-economy (E3) models is appropriately exploring the large uncertainties inherent in the modelling procedure. Without careful elucidation, analysts and policy makers alike can be misled by the precision of the model output and lured into a false sense of security at the certainty of the implied energy system transition(s). Broadly speaking, uncertainty in E3 models can be separated into input parameter uncertainty and structural uncertainty. Our focus here is on the latter, which stems from the model not fully capturing the complexity of the system it is trying to represent because, for example, it has necessarily simplified equations, a finite resolution, etc. Over the course of the ADVANCE project we have developed a technique to investigate a key element of structural uncertainty within TIAM-UCL. We have used the approach of modelling to generate alternatives to relax the cost optimality assumption that underpins the model and reformulated its objective function to explore this near optimal solution space. Our technique seeks to identify energy system transition pathways that are as diverse as possible within this near least cost space and as such assess the impact of minor, realistic deviations from cost optimal decision making.

1.3) Temporal dimension - TIAM-UCL

The model base year is 2005 with data taken from IEA Energy Balances.

The model time horizon is 95 years (2005-2100) with 5 year time steps up to 2070 and with 10 year time steps beyond. Each year is divided to six time slices + an additional peaking constraint.

Demand fractions (see Table 1.2) determine the fraction of service demand to be met during a specific period of the day in a given season (or timeslice).

The temporal resolution is determined by three seasons, summer, winter and intermediate. Each of the seasons accounts for a third of the whole year or 4 month. These timeslices are again split into night and day, where day represents 16 hours and night 8 hours (Table 1-2).

Therefore there a six timeslice possibilities of:

- summer-day,
- summer-night,
- intermediary day,
- intermediary-night,
- winter-day,
- winter-night

Table 1.2: Fraction of energy-service demands

Time slice	Month share	Day share	Fraction
ID	0.333 (4 months)	0.666 (16 hours)	0.223
IN		0.333 (8 hours)	0.111
SD	0.333	0.666	0.223
SN		0.333	0.111
WD	0.333	0.666	0.221
WN		0.333	0.111

The model is generally run with perfect foresight but can be run as myopic or stochastic though this is generally not the case.

1.4) Spatial dimension - TIAM-UCL

TIAM-UCL is a global model with 16 regions listed in the table below, each of which has their own energy system.

The TIAM-UCL model has been developed at UCL since 2010 and differs from the ETSAP-TIAM model in two ways: the first is breaking out the UK from the 15 region ETSAP-TIAM model; the second is enhancing TIAM-UCL by revising/adding new drivers and resources for all regions and adding new features.

In order to break out the UK from Western Europe (WEU) region, separate Base-Year templates were created for end-use sectors, upstream and power sectors for the UK and calibrated final energy consumption to the actual base year data 2005 for the UK and the WEU regions. The underlying data for the base year calibration in TIAM-UCL is the IEA Extended Energy Balances of OECD and non-OECD countries. This data can be accessed through the online portal https://www.ukdataservice.ac.uk/ in the UK. A database of the IEA Extended Energy Balances has been developed to import the IEA data into the data tables on the base year templates in the TIAM-UCL with a software application which allows easy aggregation of country data into regions. Energy services demands for different end-use sectors and drivers of projections of demands during the model period 2005-2100 were created for the UK region. Besides the calibration of resource and trade modules of the UK and the WEU regions, all other scenario files were also updated and calibrated.

Once the 16 region TIAM-UCL had been successfully calibrated, the model was enhanced through technical improvements such as adding new drivers, new resources, climate change policies (cap-and-trade, carbon tax), supply resource cost curves etc. Development of the database of the IEA Extended Energy Balances helped to recalibrate all 16 regions in the TIAM model to the IEA primary energy production/consumption, final consumption and electricity generation (and heat) data.

Table 1.1: Regions in TIAM-UCL

Region	Countries
Africa (AFR)	Algeria, Angola, Benin, Cameroon, Congo, Congo Republic, Egypt, Ethiopia, Gabon, Ghana, Ivory Coast, Kenya, Libya, Morocco, Mozambique, Nigeria, Other Africa, Senegal, South Africa, Sudan, Tanzania, Tunisia, Zambia, Zimbabwe
Australia (AUS)	Australia and New Zealand
Canada (CAN)	Canada
Central and South America (CSA)	Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Other Latin America, Panama, Paraguay, Peru, Trinidad-Tobago, Uruguay, Venezuela
China (CHI)	China
Eastern Europe (EEU)	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
Former Soviet Union (FSU)	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
India (IND)	India
Japan (JAP)	Japan
Mexico (MEX)	Mexico
Middle-east (MEA)	Bahrain, Cyprus, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen
Other Developing Asia (ODA)	Bangladesh, Brunei, Chinese Taipei, Indonesia, North Korea, Malaysia, Myanmar, Nepal, Other Asia, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam
South Korea (SKO)	South Korea
United Kingdom (UK)	United Kingdom
USA (USA)	United States of America
Western Europe (WEU)	Austria, Belgium, Denmark, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland

1.5) Policy - TIAM-UCL

A variety of energy and climate policies can be implemented, depending on the approach, usually by creating specific scenario files to incorporate the policy elements.

A number of general or specific policy choices can be modelled including:

- Emissions taxes,
- permit trading,
- specific technology subsidies
- Technology and/or resource constraints
- Technology and/or resource targets

2) Socio-economic drivers - TIAM-UCL

There are 42 energy-service demands for the five different end-use sectors in TIAM-UCL.

A driver is allocated to each energy service demand to project demand for future years throughout the model horizon (2005 to 2100). The driver is linked to the energy-service demand by a constant and an elasticity. Demand drivers include population, GDP, number of households, GDP per capita, GDP per household and agricultural, service and industrial drivers.

Assumptions on the development of drivers are based on several sources, which are explained in the following subsections. Assumptions on demand drivers have been substantially updated from the ESTAP-TIAM model.

2.1) Population - TIAM-UCL

Population

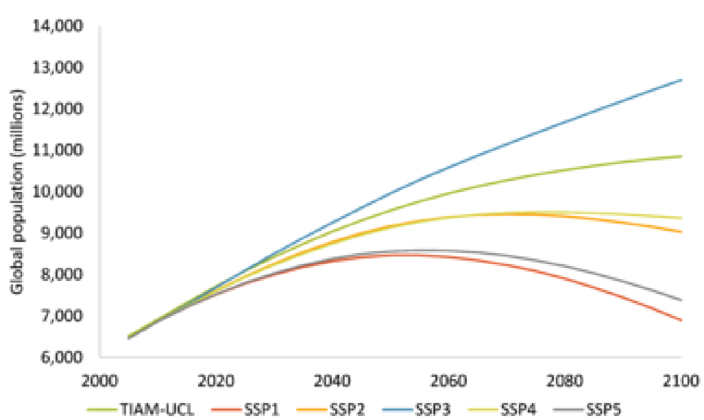
Population figures up to 2050 are based on UN estimations (UN, 2009). It is assumed that world population will increase from 6.7 billion people in 2005 to 9.3 billion people in 2050, reach the peak in 2090 with 9.8 billion and then decline slightly.

The biggest population increase over the 21st century is expected to happen in Africa, India, Other Developing Asia and the Middle East .

Under the given assumptions China, Eastern Europe, Former Soviet Union, Japan, Mexico, South Korea and Western Europe experience negative population growth rates in the second half of the 21st century.

Especially for South Korea and Japan, it is assumed that the population will shrink significantly over the course of the 21st century.

We are also able to run the various Shared Socio-economic (SSP) pathway scenarios [1] in TIAM-UCL. The standard TIAM-UCL population assumption is around halfway between SSP3 and SSP2 for population.

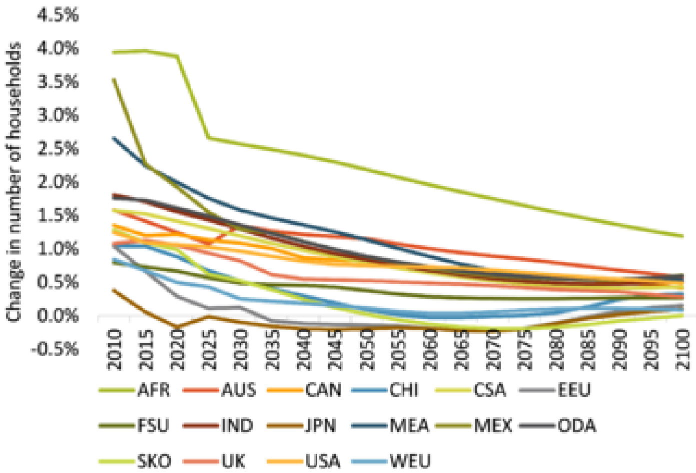


Households

The number of households is based on population estimates and occupancy rate. There exists no database for the occupancy rate for each region in the TIAM-UCL model. Therefore, the numbers in this section rely on national statistics. There are forecasts for the average household occupancy for some countries for the near future (up to 2030) from which it is possible estimate the number of households (given assumptions on population). For the longer term, it is assumed that the occupancy rate will increase in line with historic data to 1.7 to 3 persons per household, depending on the region. The reason for this range is the difference in current average persons per household, e.g. in 2005 the average Indian household consisted of 5.3 persons, while the average Western European household consisted of 2.1 persons per household.

Given these assumptions, the total number of households globally increases from 1.9 billion in 2005 to 3.4 billion in 2050 to 5.1 billion in 2100.

In order to simplify the data needed for the calculation, characteristic countries have been chosen for regions that consist of more than two countries. Those are South Africa for Africa, Brazil for Central and South America, Poland for Eastern Europe, Russia for Former Soviet Union, Iran for Middle East, Indonesia for Other Developing Asia and Germany for Western Europe.



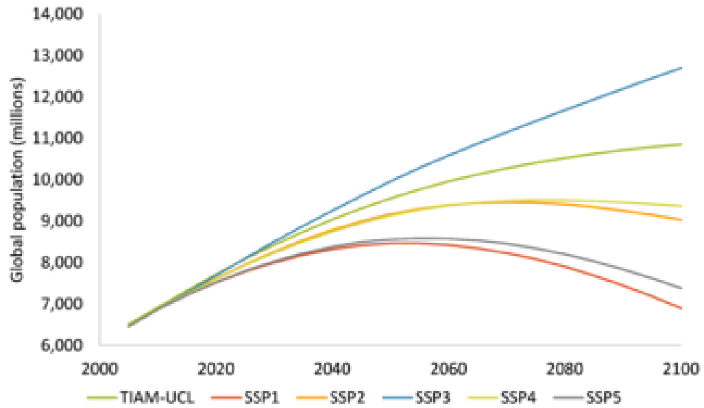
2.2) Economic activity - TIAM-UCL

GDP

Estimations of future economic growth are much more uncertain than future population growth. Few studies exist that forecast GDP up to 2100 and so unlike population assumptions, GDP figures in TIAM-UCL are not based on a single source. Economic growth rates have been compared to assumptions made for scenarios in the 4th assessment report of the IPCC (Tsuneyuki 1999) and Clarke et al. (2007). Global GDP is assumed to grow from $50 trillion in 2010 to $155 trillion in 2050 and $350 trillion in 2100 (all GDP are in 2005 US$). Current figures for 2010 have been taken from the IMF (2009).

Figures for future economic growth are based on an approximate assumption of economic convergence between regions (see Figure 3 5), i.e. that low income regions grow faster compared to high income regions. The figure shows this convergence of per capita income among world regions. The GDP per person is calculated as the ratio of GDP and population. The economic convergence is a central point in the assumptions on socio-economic drivers. The effect becomes clear when one compares the GDP per head in different regions. In 2005 India is the poorest region with a GDP per head of 10% of the world average and the USA is the richest region with 600% of the world average. In 2100 this picture changes with India having a GDP per head that has now grown to 55% of the world average and the USA being the richest country with 350% of the world average.

GDP growth rates are expected to decline over the course of the 21st century, while they remain higher for developing countries than for developed countries. Owing to the shrinking population, the growth rates for South Korea and Japan are very low and turn negative at the end of the 21st century. Growth rates for Western Europe, the UK and the United States are assumed to drop from an average of 2.2% to 1.3% p.a. in 2050. The only region that is expected to increase GDP growth rates over the first decades is Africa based on a growing population and its current low income levels. Global economic growth is approximately in the mid-range of the growth in the SSP scenarios



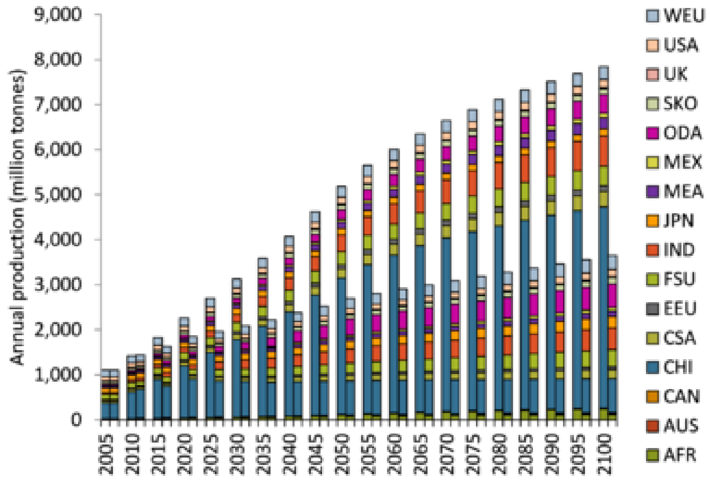
Sectoral drivers

The industrial, services and agricultural sectors have different growth drivers from all other sectors i.e. they are not directly related to growth in GDP and a decoupling factor. There are a number of reasons for this, but key is that there is expected to be a decoupling of growth in, for example, production of steel and growth in GDP that is cannot be trivially estimated by a single decoupling factor. Additionally, the industrial service demands can be interpreted as represent the production of physical quantities e.g. tonnes of steel, tonnes of aluminium etc. Projections of future production are provided by various sources, who look in detail at the array of factors that affect production and consumption levels on regional basis. These sources therefore likely provide more robust estimates of future production while also providing a more tangible projection of what is being estimated.

The projections of steel, aluminium and cement, paper and chemicals production globally used in TIAM-UCL are provided in the Figures below. These figures also shows how these compare with the projections used in ETSAP-TIAM. These quantities have been estimated using the regional per-capita consumption and productions projections from IEA up to 2050 ensuring that these balance on a global level). A single provider was used for this estimation to ensure consistency across the different metallic and non-metallic sectors. Consumption from 2050 to 2100 was then based on historical trends in per-capita consumption from 2000 to 2050, so, for example, annual aluminium consumption is assumed to trend towards 35 kg/person and steel towards 500 kg/capita as regions increase their GDP/capita. Energy-service demands rely on production and not consumption levels, which are not equal because of trade. Production to satisfy this increasing demand was thus estimated by projecting trends in production between 2010 and 2050 whilst again ensuring that consumption and production matched on a global level.

It can be seen that the new projections are in general lower than those used previously, particularly in the case of cement. These projections can be easily modified to account for different socio-economic scenarios, for example if it is assumed that material intensity will be greater or lower in the future (included within the main assumptions of the SSPs for example). The energy-service demand for agriculture is derived in a similar manner. A relationship is given between crop caloric demand/capita, protein demand/capita, and GDP/capita. This suggests that both follow an approximate square root relationship with GDP/capita (so if GDP/capita doubles protein demand and crop calorie demand increase by 41%).

TIAM-UCL requires the energy-service demand and the energy intensity of protein and crop calories are very different. However, because both crop and protein demand follow a similar relationship to GDP/capita, the GDP/capita assumption shown in the crop Figure can be used to estimate how total consumption within each region will change in the future demand. This therefore assumes a constant ratio of crop to meat calories in all regions in the future, although clearly because GDP/capita increases, the absolute level of each also increases over time. Again production levels are required for energy-service demands and not consumption. A strong assumption is therefore made whch is that the current (2005) ratio of production to consumption would remain constant in the future, a ratio that varies significantly between different regions. This assumption and projections of consumption and production can be easily modified to account for different socio-economic scenarios, say if it is assumed that global trade of agricultural goods will increase or decrease in the future.


Annual production (million tonnes)
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
9,000
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
WEU
USA
UK
SKO
ODA
MEX
MEA
JPN
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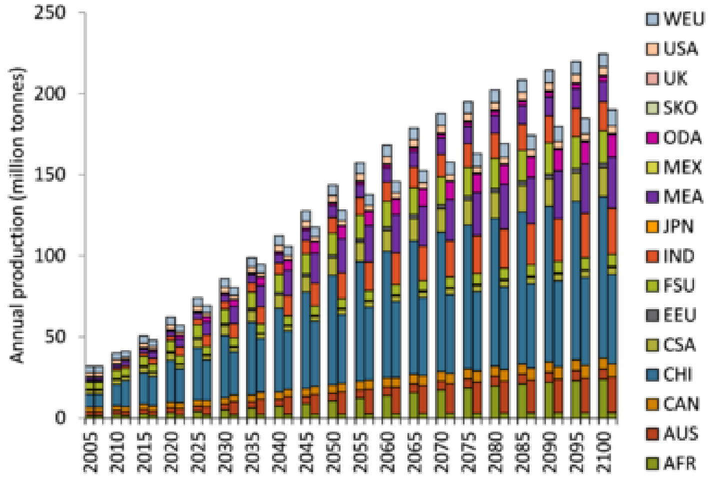
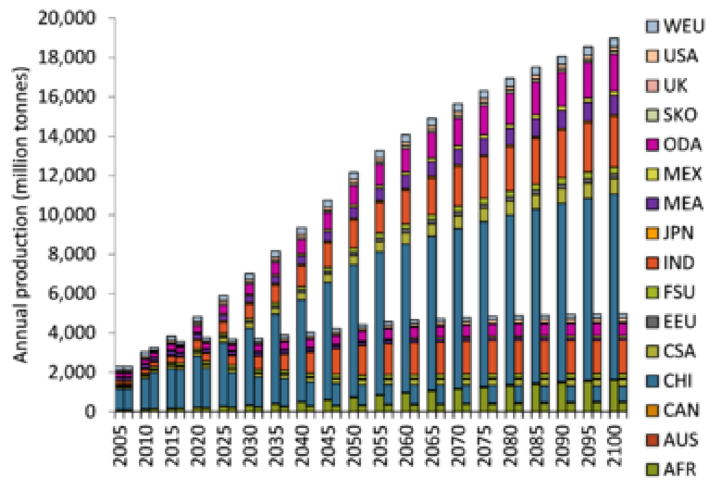
CHI
CAN
AUS
AFR


Annual production (million tonnes)
0
50
100
150
200
250
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
WEU
USA
UK
SKO
ODA
MEX
MEA
JPN
IND
FSU
EEU
CSA
CHI
CAN
AUS
AFR


Annual production (million tonnes)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
2005 2010 2015 2020 2025 2030 2035 2040 2045 2050 2055 2060 2065 2070 2075 2080 2085 2090 2095 2100
WEU
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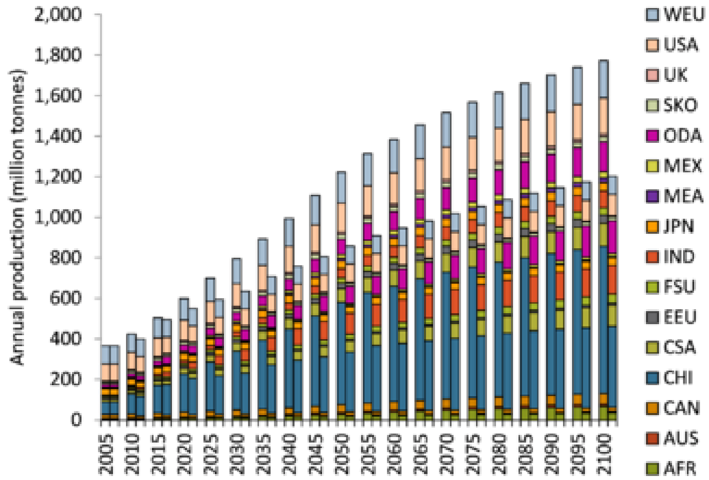
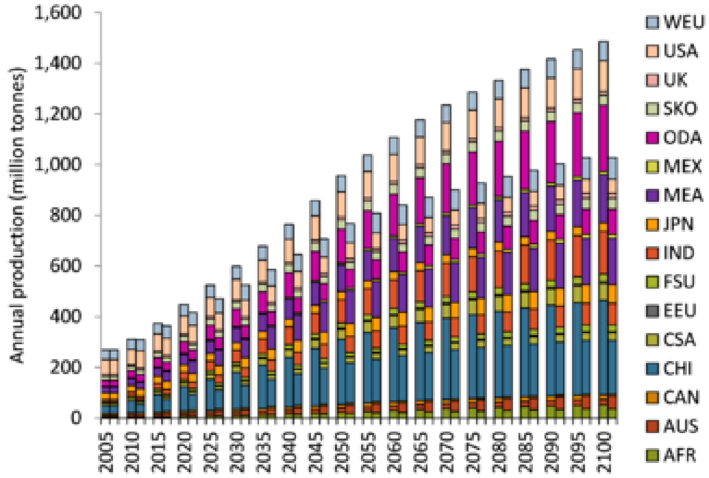
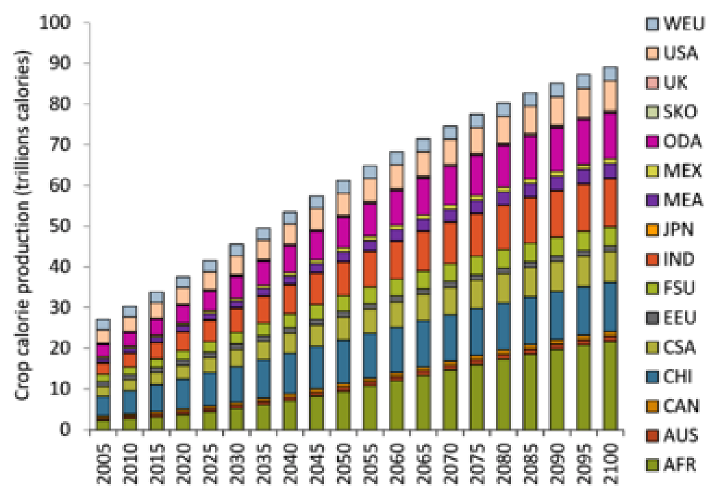






3) Macro-economy - TIAM-UCL

The economy is represented for each region by hard-linking TIAM-UCL with Macro Stand Alone (MSA) module to allow consideration of the rest of the economy beyond energy i.e. general not partial equilibrium, and endogenises demand changes.

3.1) Production system and representation of economic sectors - TIAM-UCL

We have added a simplified general equilibrium macroeconomic growth module developed by Kypreos and Lehtila (2013). Macro Stand-Alone (MSA) is a single agent; single sector, multi-regional, general equilibrium optimal growth model which maximises discounted utility of a single consumer-producer agent. GDP is comprised of consumption, investment and energy system costs. Total economic production is determined by a combination of energy, capital and labour where energy substitutes with a capital-labour composite via an elasticity of substitution parameter. Quadratic cost functions and demand decoupling factors (essentially elasticity parameters for each period and demand)are estimated from the calibration routine are fed from TIAM-UCL to MSA. MSA is then solved and the new energy demands are given back into TIAM-UCL which is then solved again. The iteration continues until the model converges, defined by the change in energy service demand variation between interactions slowing to within a specified tolerance.

3.4) Trade - TIAM-UCL

Energy Trade

Regional trade is modelled in the trade module. In the current version of TIAM-UCL, regional trade is allowed for coal, natural gas, LNG, natural gas liquid, uranium oil and oil products such as heavy fuel oil, gasoline, naphtha, diesel, energy crops and solid biomass. Emission trading under cap-and-trade policy is also modelled and the level of trading can be constrained. Trading in the base-year 2005 is calibrated to the actual energy import and export data. Base-year energy trade (import and export of fossil resources) for the UK is taken from DUKES (2010).

Table 2-3: Resources traded in the 16 region TIAM-UCL global model

Resource
Crude oil
Hard coal
Natural gas
Heavy fuel oil
Naphtha
Gasoline
Natural gas liquid
Distillates (diesel)
Liquefied natural gas
Uranium
Biomass
Bio-Fuels
Emissions permits

4) Energy - TIAM-UCL

TIAM-UCL models all primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from resource production through to their conversion, infrastructure requirements, and finally to sectoral end-use. Note, throughout this section the term hurdle rate is used to refer to a technology specific discount rate. That is, the model assumes that the payment of any capital cost is spread over an economic life that may be different from the technical life of the process, and annualized at a different rate than the overall discount rate.

4.1) Energy resource endowments - TIAM-UCL

Fossil reserves and mining technologies are presented in the Table below on Non-renewable primary resources. A supply curve for each type of the sources shown is defined within region. Each time step is characterised by the cost of the resource and the total amount of energy available at this cost.

The Resource Module contains the data which separately characterises resources which are situated in regions with members of OPEC and those resources found in all other Non-OPEC regions. The module was originally based upon that provided in ETSAP-TIAM although significant changes have been made to their characterisation and dynamics of production including: adding Arctic oil and gas, shale gas and separately considering natural bitumen and kerogen oil produced by mining and by in situ methods. Geological constraints are also imposed upon oil and gas production that represent empirical depletion rate constraints.

Table: Non-renewable primary resources

Technology Description
Oil
Existing proved plus probable reserves
Reserve growth
Undiscovered oil
Arctic oil
Natural bitumen ('oil sands') by in situ means of production
Natural bitumen ('oil sands') by mining
Extra-heavy oil
Kerogen oil by in situ means of production
Kerogen oil by mining
Natural gas liquids
Natural gas
Existing proved plus probable reserves
Reserve growth
Undiscovered gas
Arctic gas
Tight gas
Coal bed methane
Shale gas
Associated gas
Coal
Existing reserves
Additional resources
Uranium
Uranium (dummy) - Reserves

4.1.3) Bioenergy - TIAM-UCL

Biofuels impact on land-use emissions are not considered and neither are life-cycle impacts of biofuels i.e. completely carbon neutral.

Biomass used in the electricity sector is provided by two different commodities - ELCSLD (from BIOSLD) and ELCCRP (from BIOCRP). Both originate from domestic (MIN) processes: MINBIOCRP0 (producing BIOCRP) and MINBIOSLD1,2 and 3 (producing BIOSLD). In this module biomass availability is modelled for energy crops and solid biomass (Table 11 5). Energy crops and solid biomass availability data is taken from TIAM-WORLD (www.kanors.com) and some adjustment made to match the regions in the TIAM-UCL. These two biomass resources are traded, transportation cost is presented in trade module. The domestic production bounds for 2005 can be found in the BY UPS templates. Concerning costs, all regions have the same COST for the three tranches of BIOSLD (at 0.63, 1.88 and 3.13). For BIOCRP, resource costs differ between regions although the basis for this differential is not clear. They range between 1.38 in India to 3.65 in ODA. All costs remain the same over the time horizon.

4.1.4) Non-biomass renewables - TIAM-UCL

Table 3.1.2 presents technology for renewable resources that are modelled in the TIAM-UCL. Renewable electricity resources such as hydro, geothermal, solar, tidal and wave are modelled. Solid biomass, energy crops, municipal waste and landfill gas are also modelled. Biomass technologies compete directly at energy service demand level with fossil fuel technologies. No distinction is made between OPEC and Non-OPEC countries for primary and secondary biomass production. Annual availability of renewable resources are controlled in different scenario files. Renewable production can be constrained through annual bounds on capacity and growth constraints.

Table 3.1.2: Renewable primary resources

Technology Description
Hydro potential
Geothermal potential
Solar potential
Tide potential
Wind potential
Prod of Solid biomass
Prod of Industrial wastes
Prod of Municipal wastes
Prod of Gas from biomass (landfill gas)
Prod of Energy crop

4.2) Energy conversion - TIAM-UCL

Energy conversion technologies in TIAM-UCL are undertaken by various distinct processes and are generally characterized by a number of data inputs including:

- investment costs

- operation and maintenance costs

- lifetime

- efficiency

- environmental outputs (CO2)

- growth constraints

Also, electricity grids are not explicitly modelled, with no capacity limits or investment requirements for system infrastructure. Two commodities are produced to represent generation from centralised (ELCC) and decentralised (ELCD) technologies. Distribution losses are modelled by commodity efficiency for ELCC (using parameter COM_IE). They reflect regional differences in the base year but by 2100 are the same across all regions. Electricity supply is tracked at a DAYNITE timeslice resolution. This allows for simplistic modelling of the load curve, representing when consumers demand electricity (see section 3 on demand drivers for more information). DAYNITE time-slices total 6 periods, representing day and night in the three (equal length) seasons (summer, winter, intermediate).

4.2.1) Electricity - TIAM-UCL

Conversion

The electricity and heat generation sector represents many different technology types, using a wide range of fossil-based and renewables resources. The existing system is represented in generic terms whilst the options for future investments are characterised in more detail. Annual electricity and heat supply is temporally disaggregated across six periods (or *time slices*), based on three season and two diurnal periods (Day / night) to represent changes in load based on sector demand profiles.

Electricity generation plant are additionally categorised as providing electricity to the centralised or decentralised grid (CEN or DCN). Decentralised producers tend to be small scale, connected to the distribution network or serving local grids, and produce one commodity in the model while centralised producers, connected to transmission network, produce a seperate commodity.

The electricity sector Base-Year template is used to calibrate the base-year electricity and heat generation. In the Base-Year template (providing information on existing plant), characterisation of plants is fairly generic, with all production of electricity categorised as ELC-CEN. Off-grid production (via micro-generation technologies) is not explicitly captured in the model, with small-scale generation represented in the decentralised producer group.

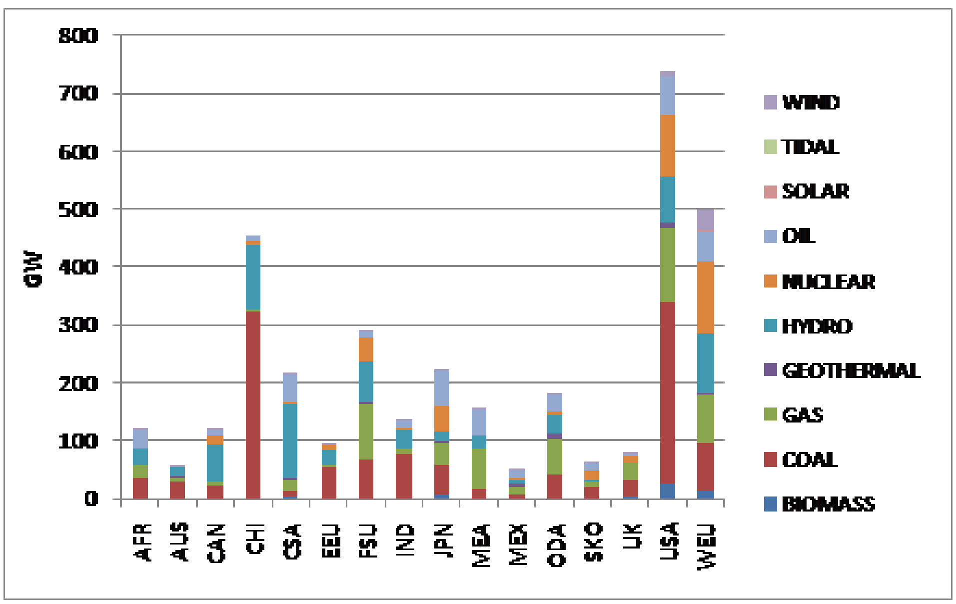


Figure: Existing Electricity Generation Capacity by Region in 2005 (Model base year), GW

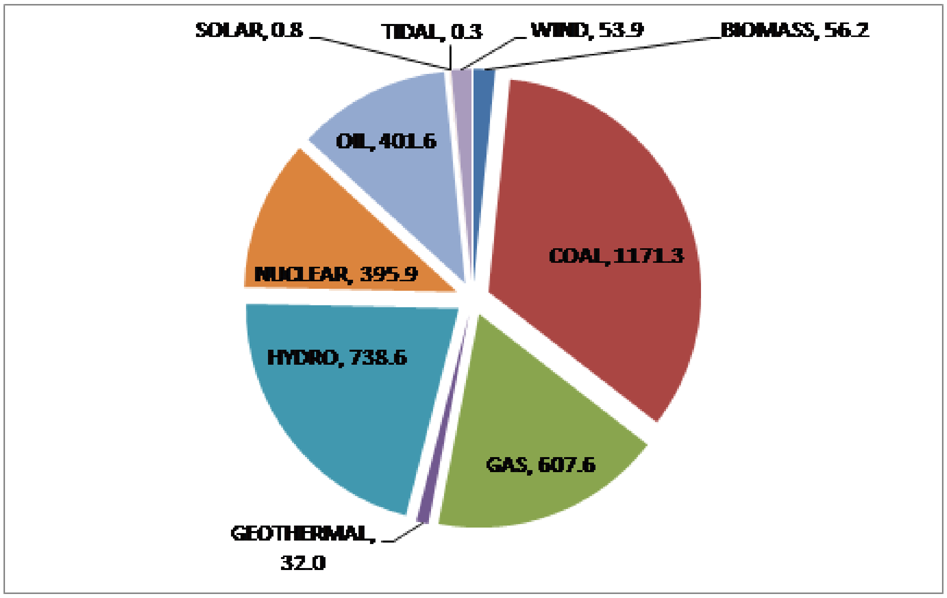


Figure: Existing Electricity Generation Capacity by Type in 2005 (Model base year), GW

New technologies

Key technology options

New electricity generation technologies are listed in Table.

Table: New technology options for electricity

Technology Group	**Model Technology Description**
Coal	Atmospheric Fl Bed.
	Air Blown IGCC.
	Oxygen Blown IGCC.
	Pressurized Fl Bed.
	Pulverized Coal.
Gas	Gas Steam.
	Fuel Cells.
Dual gas / oil	Gas_Oil Comb Cycle.
	Advanced Gas_Oil Turbine.
Oil	Oil Steam.
	Generic Dist Gen for Base Load.
	Generic Dist Gen for Peak Load.
Nuclear	Advanced Nuclear.
	Fusion Nuclear.
	Advanced Nuclear LWR.
	Advanced Nuclear PBMR.
Hydro*	Generic Impoundment Hydro.
	Generic Impoundment Hydro.
	Generic Impoundment Hydro.
	Generic Impoundment Hydro.
	Generic Impoundment Hydro.
	Generic ROR Hydro.
Biomass	Crop Direct Combustion.
	Crop Gasification.
	Biogas from Waste.
	MSW Direct Combustion.
	Sld Biomass Direct Combustion.
	Sld Biomass Gasification.
	Sld Biomass Direct Combustion.Decentralized
	Sld Biomass Gasification.Decentralized
Geothermal	Shallow.
	Deep.
	Very deep.
Solar PV*	CEN.PV.T0
	CEN.PV.
	CEN.PV.T1
	CEN.PV.T2
	CEN.PV.T3
	CEN.PV.T4
	CEN.PV.T5
	DCN.PV.T0

	DCN.PV.
	DCN.PV.T1
	DCN.PV.T2
	PV.T3
	PV.T4
	PV.T5
Solar thermal	CEN.Thermal.
Wind*	CEN.
	CEN.Offshore.
	CEN.Onshore.
	DCN.Onshore.

- Different tranches of renewable technologies represent differences in the cost of resources (hydro) or quality of the resource (wind, solar).

An important element is the transformation element which allows for regional differences to be introduced without having to duplicate technologies. For the electricity sector, the following parameters are controlled, and varied by region:

- Costs parameters (INVCOST, FIXOM and VAROM). Operation and maintenance costs tend to be lower in developing regions, as do investment cost where those regions have a technology manufacturing base e.g. China.
- Technology discount rate set to 10%, except for solar technologies, where the rate is higher for some regions. Higher rates are typically used for developing regions.
- Seasonal AFs are set by region for solar technologies, accounting for different insolation values.
- Construction time is provided for hydro and nuclear technologies - 10 years for nuclear and hydro (dam) and 5 years for hydro (run-of-river). No differentiation is made between regions.

Further work is required to include new CHP technologies, which are not available for public system or industry investment.

An overview of the key parameters for the different technology groups is shown in below.

Table: Overview of technology characteristics by technology group (for WEU region)

Technology Group	Efficiency % (range)		Investment cost $/kW (range)		Comment
	2005	**2050**	**2005**	**2050**	
Coal	40-49	40-49	1430-1870	1265-1662	
Gas / Dual	37-57	37-57	360-1000	300-1000	Lower cost and higher efficiency values represent combined cycle technology
Oil	31-35	31-35	660-1045	660-1045	
Nuclear			1760-1870	1760-1870	Fusion costs set at 3300 $/kW
Hydro			1650-6050	1540-5400	Five dam-based technologies reflecting different cost of resource
Biomass	33-34	33-34	1870-2200	1870-2200	MSW plant significantly higher at 3850 $/kW
Geothermal			1925-2780	1650-2310	Three geothermal technologies reflecting different cost of resource
Solar PV			7150-11000	1485-3025	Low cost is centralised plant and high cost decentralised plant. Technology resource tranched on basis of AFs
Solar thermal			13321	13321	Single technology with no evolution on costs
Wind			1065-1650	880-1310	One backstop, one offshore (CEN) and 2 onshore (one is CEN and one is DCN) technologies. Offshore tech. represents the high costs.

Power plants with CCS technologies

For low carbon analyses, sequestration technologies in the electricity generation sector are very important. The first five technologies listed have vintages for 2010, 2020 and 2030.

Table: Overview of Power plant with CCS technology characteristics

Model Technology Description	Investment cost ($/kW)	Efficiency (%)
NGCC+Oxyfueling	950-1250	48-55
NGCC+CO2 removal from flue gas	800-1000	49-57
IGCC+CO2 removal from input gas	1800-2300	40-48
Conventional Pulverized Coal+Oxyfueling	1900-2400	37-44
Conventional Pulverized Coal+CO2 removal from flue gas	1850-2250	38-44
SOFC (COAL) +CO2 removal - 2030	2200	48
SOFC (GAS) +CO2 removal - 2020	1600	58
Crop Direct Combustion. With CCS	2125	33
Crop Gasification.with CCS	2500	34
Sld Biomass Direct Combustion.with CCS	1700	33
Sld Biomass Gasification.with CCS	2420	34

The fossil-based plants produce SNKELCCO2, a 'dummy' commodity which then goes to the different storage technologies. Biomass plants with sequestration produce SNKTOTCO2, differentiated as technologies that capture CO2 from the atmosphere (negative emissions). The range of storage technologies in the model are listed below.

Types of storage technologies

Removal by Enhanced Coalbed Meth recov <1000 m

Removal by Enhanced Coalbed Meth recov >1000 m

Removal by Depl gas fields (offshore)

Removal by Depl gas fields (onshore)

Removal by Storage in the deep ocean

Removal by Depl oil fields (offshore)

Removal by Depl oil fields (onshore)

Removal by Deep saline aquifers

Removal by Enhanced Oil Recovery

Mineralization for CO2 storage

4.2.2) Heat - TIAM-UCL

Heat technologies are respresented as

- Public CHP plant, providing electricity to the grid and heat to local distict heating networks
- Sector CHP plant (autoproducers), providing electricity and heat to specific industries.
- Public heat generation plant (heat only plants), providing heat to local distribution networks

4.2.3) Gaseous fuels - TIAM-UCL

Alternative fuels

Table 3.2.4 contains technologies for the production of alternative fuels. The technologies are split into two groups: 1) Ethanol and methanol production, either from coal or biomass and 2) Fischer-Tropsch processes, producing oil products from coal, gas and biomass.

Table 3.2.4: Alternative fuel technologies

Model Technology Description
Ethanol from biomass
Cellulose ethanol plant
Methanol from Bioliquids
Methanol from coal
Methanol from coal with CO2 capture
Methanol from natural gas
Methanol from natural gas with CCS
FT fuels from natural gas
FT fuels from natural gas with CCS
FT fuels from coal
FT fuels from coal with CCS
FT fuels from coal low biomass and coal co production
FT fuels low biomass and coal co production with CCS
FT fuels high biomass and coal co production
FT fuels high biomass and coal co production with CCS
FT fuels solid biomass
FT fuels solid biomass with CCS

Hydrogen

New technologies include those used for hydrogen production and demand technologies in the transport sector that consume hydrogen. Production technologies are generic in nature and are defined by the type of fuel used - coal, natural gas, electricity and biomass.

There are also technologies, available from 2020, that allow for mixing of hydrogen into the natural gas supply to different sectors. This mix is fixed at 15% hydrogen / 85% natural gas. A single distribution technology allows for hydrogen transport, with costs developed on the basis of unit of energy transported (using VAROM).

Table 3.2.5: Hydrogen production and supply technologies

Model Technology Description
Hydrogen from Brown coal
Hydrogen from Hard coal
Electrolysis
Hydrogen from NGA
Hydrogen from NGA - Decentralized
Hydrogen from biomass gasification
Mix of Gas and Hydrogen - For COM
Mix of Gas and Hydrogen - For IND
Mix of Gas and Hydrogen - For RES
Distribution of hydrogen

Hydrogen technologies for cars and light duty trucks are included in the model, with different types based on the use of combustion, hybrid or fuel cell technology. The associated Trans file puts different hurdle rates on these technologies, assuming 15% for developed regions and 30% for developing regions such as Africa. The Trans file is also used to adjust efficiencies and costs across all regions, for both transport and production technologies.

Sequestration

Sequestration technologies and storage options mainly relate to the electricity sector, and are described in the relevant sector chapter of this report.

There are two technologies that allow for the capture of CO_2 emissions (process-based) in the upstream sector. The costs of such 'dummy' capture technologies are modelled simply, using variable costs of 0.001 (equivalent to \$1/tCO_2).

Another set of important technologies for integrated climate modelling are those that relate to emissions and removals by the forestry sector. Labelled SINKAF*. The levels of emissions and removals and the associated costs are controlled by the Trans file and are based on assumptions used in the EMF analysis. Finally, atmospheric CO2 may be partly absorbed and fixed by biological sinks such as forests; the model has six options for forestation and avoided deforestation, as described in Sathaye et al. (2005) and adopted by the Energy Modelling Forum, EMF-21 and 22 groups.

Land-use CO_2

The SubRes file *LUCO2* defines a single technology that emits fixed levels of emissions by region each period. It is net CO2 emissions from deforestation and forest degradation. It does not include emissions from land use. The levels are calculated in the associated Trans file. The global emission level in 2005 is estimated at 2.7 GtCO_2 per year, which decreases to 0.1 GtCO_2 by 2100.Allocation by region is based on distribution of agricultural managed land. It is assumed that LULUCF emissions for UK is zero and therefore, WEU region's LULUCF emission has not been changed. There are scenarios in the model with reduced emissions from deforestation based on the EMF 21 study scenarios.

Grid and infrastructure

No representation of grids in TIAM-UCL except Electricity generation can be centralised or decentralised (CEN or DCN). A generic cost and efficiency loss associated with distribution are included for Gas pipelines and electricity.

The range of CO2 storage technologies in the model are listed below.

Table 3.2.6: Types of storage technologies

Model Technology Description
Removal by Enhanced Coalbed Meth recov <1000 m
Removal by Enhanced Coalbed Meth recov >1000 m
Removal by Depl gas fields (offshore)
Removal by Depl gas fields (onshore)
Removal by Storage in the deep ocean
Removal by Depl oil fields (offshore)
Removal by Depl oil fields (onshore)
Removal by Deep saline aquifers
Removal by Enhanced Oil Recovery
Mineralization for CO2 storage

4.3) Energy end-use - TIAM-UCL

Energy end-use demand is broken down into the following sectors: Transport, Residential and Commercial, Industry and Other (Agriculture). Each sector is composed of a number of energy service demands that map to specific components of that sector, e.g. residential hot water. The temporal trajectory of these energy service demands are linked to underlying demand drivers such as GDP or population, as will be detailed later (see Energy demand - TIAM-UCL (http://themasites.pbl.nl/models/advance/index.php/Energy_demand_-_TIAM-UCL)).

4.3.1) Transport - TIAM-UCL

Energy services demand

The transportation sector is characterized by 14 energy-services plus one non-energy use demand segment (Table 3.3.1). Six of the energy-services are considered as generic demands: international and domestic aviation, freight and passenger rail transportation, domestic and international navigation. All other energy-services are for road transport. The non-energy use is predominately the demand lubricants. Demand for road transport energy-services is expressed in billion vehicle km (b-vkm) and others are in PJ. The model projects energy-services demands for each region.

Table 3.3.1: Energy-service demands in transport sector

Energy-service sectors
Domestic Aviation
International Aviation
Road Bus Demand
Road Commercial Trucks Demand
Road Three Wheels Demand
Road Heavy Trucks Demand
Road Light Vehicle Demand
Road Medium Trucks Demand
Road Auto Demand
Road Two Wheels Demand
Rail-Freight
Rail-Passengers
Domestic Internal Navigation
International Navigation
Non-energy use

Table 3.3.2 presents the list of transport fuels available to meet the base-year energy-service demand in each transport subsector. Diesel and gasoline are considered as the conventional fuels and the other are alternative fuels which are introduced later. Jet fuel and electricity are available to meet aviation demand.

Table 3.3.2: transport fuels

Fuel
diesel
electricity
ethanol
gasoline
LPG
methanol
natural gas

For each end-use, a number of new (i.e. available after the base year of 2005) technologies are in competition to satisfy the energy-services demand for future years. Efficiency and cost of these technologies improve over the period with vintages. These technologies progressively replace the existing ones (i.e. those used in the base year) and they are characterized by the same type of parameters such as efficiency, and investment cost. There are many new technologies available for the road transport sector whereas technological detail is very limited in rail, shipping and aviation modes. Investment and O&M costs shown are US dollar reference prices. They are multiplied by regionally specific factors for each region. Technology and regional specific hurdle rates, which are used to annualise the investment cost, are also applied.

As an outcome of the ADVANCE project, TIAM-UCL can now explicitly distinguish up to 27 different types of vehicle users (e.g., urban or rural, frequent or less frequent, risk averse or novelty-seeking). Non-financial vehicle attributes including novelty, range, and refueling availability can also now influence vehicle choices in an explicit way. Consumers' preferences for these attributes have been monetized drawing on the expertise of a detailed transport sector model (MA3T). These 'intangible' costs and benefits have been included alongside pure financial costs in the investment cost calculations influencing vehicle choice. Importantly, these additional terms vary uniquely by consumer type, by region, and by vehicle technology.

4.3.2) Residential and commercial sectors - TIAM-UCL

Residential sector

Residential sector final energy consumption calibration is carried out in the Base-Year template for residential, commercial and agriculture sectors. The template uses IEA residential sector final consumption data for the base-year 2005. It also includes details for residential sector fuels and all existing technologies in residential sector. The template also captures residential sector emissions. All new technologies that are available after the first year (base-year) are modelled separately. Selected energy-services in the residential sector also have demand data at the sub-regional level for certain regions in order to have different growth rates.

Energy service demands

The residential sector includes 11 energy-services as presented in Table 3-4-3. All energy-service demands are in PJ. In the residential sector, some segments are identified using more than one abbreviation, which means that the demand can be disaggregated in four or less sub-regions. Currently, USA and CAN have four and three geographic regions, respectively, while AFR, CHI, IND, MEA and MEX each have two sub-regions, corresponding to rural and urban areas. When no sub-regions have been defined, the abbreviation for sub-region 1 is used by default. Energy service demands are projected to 2100 using general economic and demographic drivers (population, GDP and GDP per capita). To develop projections of future energy-service demands, estimates of drivers are used in conjunction with user assumptions on the topic of service demand sensitivity to these drivers (see Section on demand projections and drivers). Growth rates for residential lighting are relatively high in selected sub-regions in the developing world. This is because of very low level of electrification at present (base-year) in these sub-regions.

Table 3.4.3: Residential sector energy-services

Energy-Service
Residential Cooling
Residential Clothes Drying
Residential Clothes Washing
Residential Dishwashing
Residential Other Electric
Residential Space Heat
Residential Hot Water
Residential Cooking
Residential Lighting
Residential Refrigeration
Residential Others

The same fuels (both Existing and New) are used in both the Residential and Commercial sectors.

Technologies

Residential sector existing end-use technologies are modelled in the Base-Year templates. No investment can be made in existing technologies. New technologies progressively replace the existing ones as they reach the end of their technology life assumptions. For each end-use energy-service, a number of existing technologies are in competition to satisfy the demand. They are characterized by an efficiency, an annual utilization factor, a lifetime, operation costs, and six seasonal share coefficients (summer-day, summer-night, intermediary-day, intermediary-night, winter-day, winter-night). The sum product of the final energy consumption and the efficiency of technologies give the base-year demand value. Region specific hurdle rates, which are used to annualise investment cost of the residential end-use technologies, has been applied to residential sector technologies.

Commercial Sector

Commercial sector base-year final energy consumption is calibrated in the residential sector Base-Year template, which has separate work sheets for commercial sector IEA data, sector fuel data, end-use technology data and emissions data. There are separate sheets available for technology data for each energy-service demand.

Energy services demand

The commercial sector includes eight energy service demands for each region as presented in Table 3.4.1. Some segments of the commercial sector energy-services are identified using more than one code, which means that the demand can be disaggregated in four or less sub-regions.When no sub-regions have been defined, the codes for sub-region 1 are used by default. Currently, USA and CAN have four and three geographic regions, respectively, while AFR, CHI, IND, MEA and MEX each have two sub-regions, corresponding to rural and urban areas. The energy-service demands for the future period (2005-2100) are projected using appropriate drivers and elasticities.

Table 3.4.1: Energy-services in commercial sector

Energy-service
Commercial Cooling
Commercial Cooking
Commercial Space Heat
Commercial Hot Water
Commercial Lighting
Commercial Office Equipment
Commercial Refrigeration

Sector fuels

Table 3.4.2 contains details of existing fuel technologies (each also has a new fuel technology vintage) for the commercial sector. Commercial sector emissions factor to capture commercial sector emissions are also included in the Base-Year template.

Table 3.4.2: commercial sector fuel technologies-existing

Technology Description
Fuel Tech - Natural Gas Mix (COM)
Fuel Tech - Diesel (COM)
Fuel Tech - Heavy Fuel Oil (COM)
Fuel Tech - Kerosene (COM)
Fuel Tech - Coal (COM) - Existing
Fuel Tech - Liquefied Petroleum Gases (COM)
Fuel Tech - Biofuels (COM)
Fuel Tech - Geothermal (COM)
Fuel Tech - Solar (COM)
Fuel Tech - Electricity (COM)
Fuel Tech - Heat (COM)

Technologies

There are a number of existing technologies modelled for each energy service demand in the Base-Year template for each region and sub-region. For each energy service demand, a number of technologies are in competition to satisfy the demand. They are characterized by an efficiency, an annual utilization factor, a lifetime, operation costs, and six seasonal share coefficients (summer-day, summer-night, intermediary-day, intermediary-night, winter-day, winter-night). A list of new technologies are modelled. These technologies are available after the first period (base-year) and progressively replace the existing ones as they reach the end of their technology life assumptions. In addition to parameters specified for existing technologies, new technology descriptions include information such as technology cost. The parameters such as cost, efficiency, etc., can improve over the years with vintages. Regional specific hurdle rates, which is used to annualised the investment cost, are used for commercial end-use technologies.

4.3.3) Industrial sector - TIAM-UCL

Energy-service demands

The industrial sector is characterized by 6 demand segments, each representing either the physical output of the industry or the total energy requirement (**Table 3.5.1)**. There are also one demand for 'Other non-specified energy consumption (ONO)', one for 'Industrial and Other non-energy uses (NEO)' and one for 'Other Industrial consumption (I0I)', which are considered as a generic demands. The last one (I0I) has been added for minor calibration purposes and is generally not used. There are different technologies and fuels modelled for supplying steam, process heat, machine drives and electro-chemical process for each energy-service demand in the Base-year templates.

Table 3.5.1: Industry sector energy-services

Code	Energy-service demand	Unit
I0I	Other Industrial consumption	PJ
ICH	Chemicals	PJ
IIS	Iron and Steel	Mt
ILP	Pulp and Paper	Mt
INF	Non-ferrous metals	Mt
INM	Non Metals	PJ
NEU	Other Industries	PJ
NEO	Industrial and Other Non Energy Uses	PJ
ONO	Other non-specified consumption	PJ

Energy service demands are projected to 2100 using general economic and demographic drivers (http://themasites.pbl.nl/models/advance/index.php/Energy_demand_-_TIAM-UCL) population, GDP, GDP per capita and sectoral output). To develop projections of future energy service demands, estimates of drivers are used in conjunction with user assumptions on the topic of service demand sensitivity to these drivers. Projected industry sector energy-service demands at a global level are presented in **Figure 3.5.1**. Similar tables have been generated for each region. Industry sector has relatively high growth in China as compared to other regions.

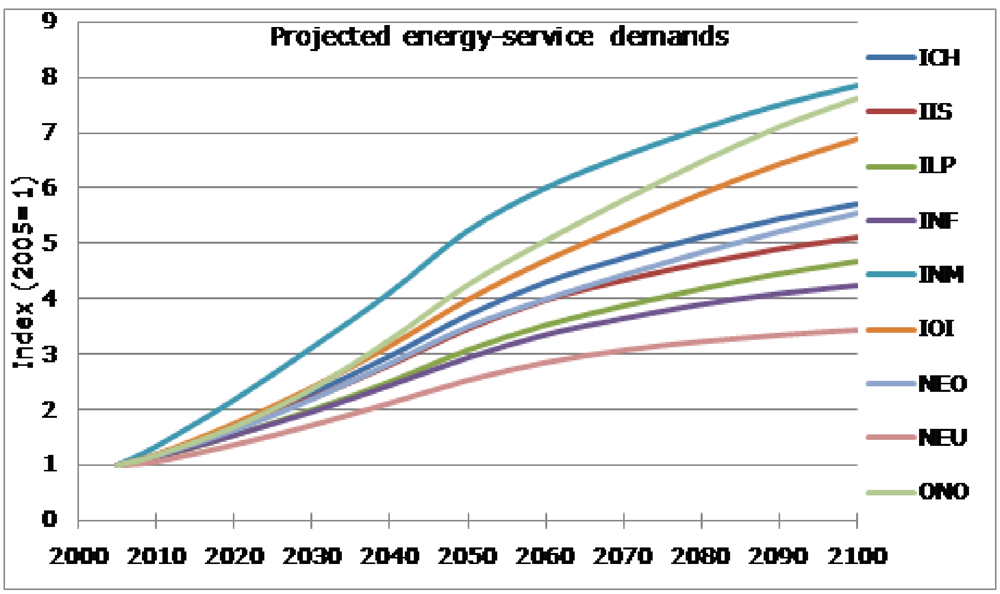


Figure 3.5.1: projected industry sector energy-service demands at global level

There are hundreds of technologies modelled in the industry sector to meet the energy-service demands. For each energy-services of each industry, a number of existing technologies are in competition to satisfy energy-service demand. They are characterized by an efficiency, an annual utilization factor, a lifetime, operation costs, and six seasonal share coefficients (summer-day, summer-night, intermediary day, intermediary-night, winter-day, winter-night). The technologies included in the Base-Year template are the existing technologies to meet the base-year demand and the residual capacities can be used till end of their life period. No new investments are allowed in the existing technologies in any sector. . These technologies progressively replace the existing ones and they are characterized by the same type of parameters such as efficiency, and investment cost. Regional specific hurdle rates (http://themasites.pbl.nl/models/advance/index.php/Energy_-_TIAM-UCL) are applies to industry sector new technologies as shown in **Figure 3.5.2**. It varies from 10% (developed countries) to 20% (least developed countries).

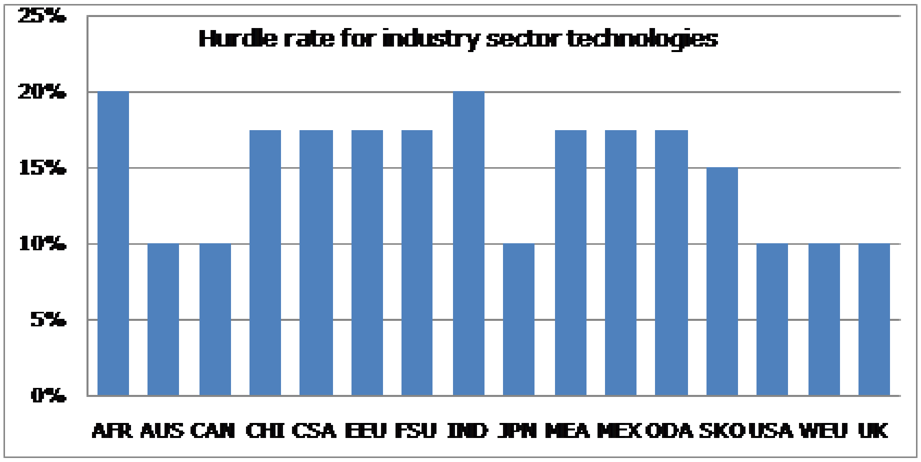


Figure 3.5.2: Regional specific hurdle rate for industry sector technologies

4.3.4) Other end-use - TIAM-UCL

Agriculture

Energy services demand

Energy-service demand in the agricultural sector is represented by a single demand segment and projected using the driver 'agricultural sector output', which is based on GDP per capita and population, for each region. **Figure 3.6.1** presents the projected energy-service demand by region. Note that there are no new technologies associated with the generic demand (AGR). In this sector, it is assumed that increases in agricultural output result in proportionate increases in energy input.

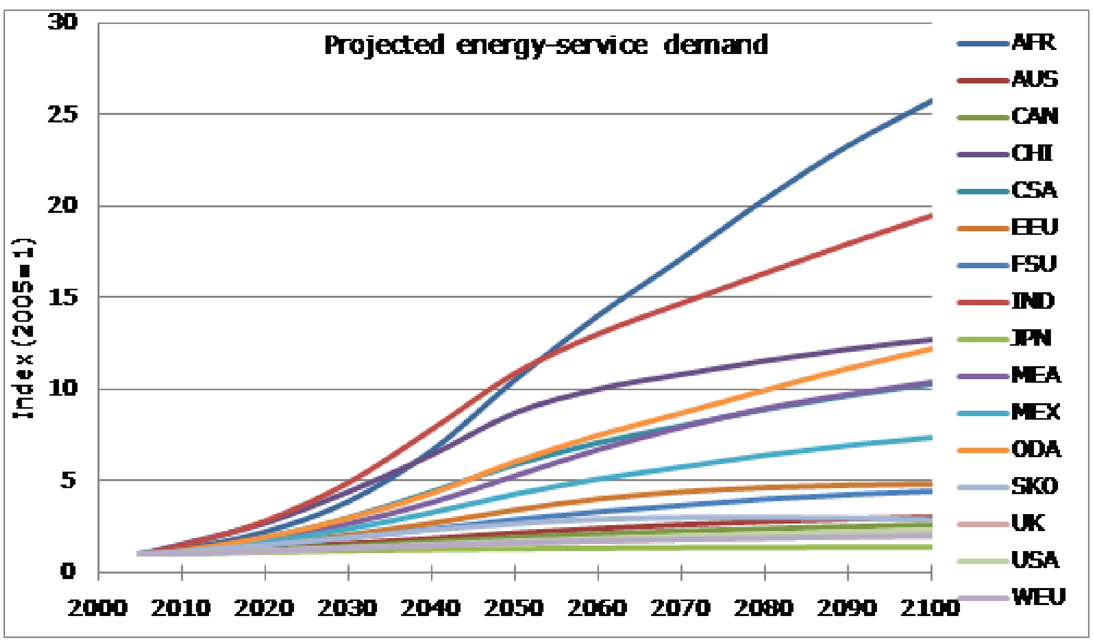


Figure 3.6.1: Agriculture energy-service demand projection by region

Sector fuels

Sectoral fuel technologies are modelled in the sheet AGR_Fuels in the residential Base-Year template as shown in **Table 3.6.1.** The fuels are aggregated into 13 categories consumed in the agriculture sector. Aggregation ratios are based on data provided by the IEA database. The technologies created to produce aggregated fuels (Fuel Tech) are named uniformly using the name of the aggregated fuels as specified in the column Commodity OUT plus three zero (000 for existing technology in the base-year). Their description changes according to the fuel (e.g. Fuel Tech - Coal (AGR) or Fuel Tech - Natural Gas (AGR). The fractional shares of the disaggregated fuels (Commodity IN) used to produce an aggregated fuel (Commodity OUT) are calculated from their consumption over the total for this category, as given in the IEA database.

Table 3.6.1: Agriculture sector fuel technologies-existing

Technology Description
Fuel Tech - Natural Gas Mix (AGR)
Fuel Tech - Natural Gas (AGR)
Fuel Tech - Diesel (AGR)
Fuel Tech - Gasoline (AGR)
Fuel Tech - Heavy Fuel Oil (AGR)
Fuel Tech - Kerosene (AGR)
Fuel Tech - Coal (AGR)
Fuel Tech - Liquified Petroleum Gases (AGR)
Fuel Tech - Biofuels (AGR)
Fuel Tech - Geothermal (AGR)
Fuel Tech - Solar (AGR)
Fuel Tech - Electricity (AGR)
Fuel Tech - Heat (AGR)

Base-year calibration

IEA energy balance provides agriculture energy consumption by fuels. Since agriculture sector is defined with a single energy-service, there is no need for that split of fuel consumptions into different sub-sector as we did for other end-use sector. Fuels in the IEA energy balance has been aggregated into 13 fuels (commodity) as defined in the sector fuel table **(Table 3.6.1)**. The energy mix of Base-year global agriculture final energy consumption (7,283 PJ) is presented in **Figure 3.6.2** at a global level.

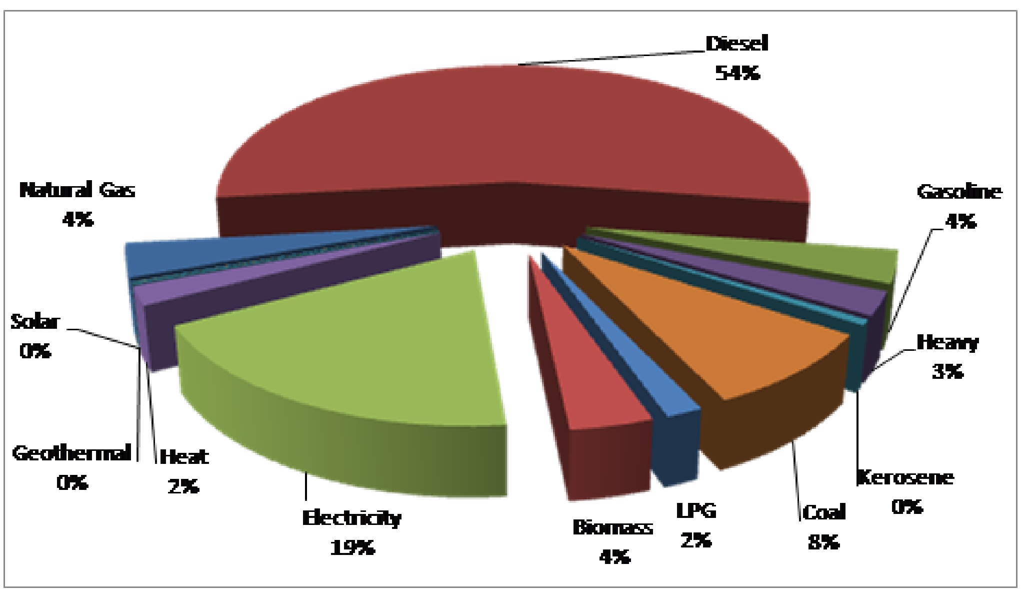


Figure 3.6.2: Base-year agriculture energy consumption mix by fuel

4.4) Energy demand - TIAM-UCL

Demand drivers (population, GDP, family units, etc.) are obtained externally, via other models or from other sources (e.g. UN statistics, World Bank, IEA). Energy-service demands and respective drivers in the TIAM-UCL are presented in Table **2-1**. The demands for energy services are linked to the drivers' projections via elasticities, see bellow. These elasticities of demands are intended to reflect changing patterns in energy service demands in relation to socio-economic growth, such as saturation in some energy end-use demands, increased urbanization, or changes in consumption patterns once the basic needs are satisfied. The energy-service demands for future years are projected using the following relationship:

$$Demand_t = Demand_{t-1} \times k \times driver^{elasticity}$$

Where *k* is a constant equal to 1 for most of the energy services demand. The constant *k* is population and number of households when the driver is GDP per Person (GDPP) and GDP per Household (GDPPHOU) respectively.

Table 2-1: Energy-services demand and respective drivers

Code	Description	Unit	Driver
ICH	Chemicals	PJ	PCHEM
IIS	Iron and Steel	Mt	PISNF
INF	Non-ferrous metals	Mt	PISNF
INM	Non Metals	PJ	POEI
ILP	Pulp and Paper	Mt	POEI
IOI	Other Industries	PJ	POI
I00	Other Industrial consumption	PJ	Constant
NEO	Industrial and Other Non Energy Uses	PJ	GDP
ONO	Other non-specified consumption	PJ	GDP
AGR	Agricultural demand	PJ	PAGR
CC1	Commercial Cooling - Region 1	PJ	PSER
CCK	Commercial Cooking	PJ	PSER
CH1	Commercial Space Heat - Region 1	PJ	PSER
CHW	Commercial Hot Water	PJ	PSER
CLA	Commercial Lighting	PJ	PSER
COE	Commercial Office Equipment	PJ	PSER
CRF	Commercial Refrigeration	PJ	PSER
RC1	Residential Cooling - Region 1	PJ	HOU/GDPPHOU*
RCD	Residential Clothes Drying	PJ	HOU/GDPPHOU*
RCW	Residential Clothes Washing	PJ	HOU/GDPPHOU*
RDW	Residential Dishwashing	PJ	HOU/GDPPHOU*
REA	Residential Other Electric	PJ	HOU/GDPPHOU*
RH1	Residential Space Heat - Region 1	PJ	HOU
RHW	Residential Hot Water	PJ	POP
RK1	Residential Cooking - Region 1	PJ	POP
RL1	Residential Lighting - Region 1	PJ	GDPP
RRF	Residential Refrigeration	PJ	HOU/GDPPHOU*
NEU	Non Energy Uses	PJ	GDP
TAD	Domestic Aviation	PJ	GDP
TAI	International Aviation	PJ	GDP
TRB	Road Bus Demand	Bv-km	POP
TRC	Road Commercial Trucks Demand	Bv-km	GDP
TRE	Road Three Wheels Demand	Bv-km	POP
TRH	Road Heavy Trucks Demand	Bv-km	GDP
TRL	Road Light Vehicle Demand	Bv-km	GDP
TRM	Road Medium Trucks Demand	Bv-km	GDP
TRT	Road Auto Demand	Bv-km	GDPP
TRW	Road Two Wheels Demand	Bv-km	POP
TTF	Rail-Freight	PJ	GDP
TTP	Rail-Passengers	PJ	POP
TWD	Domestic Internal Navigation	PJ	GDP

TWI	International Navigation	PJ	GDP

- The driver is GDPPHOU for AFR, CHI, CSA, EEU, FSU, IND, MEA, MEX, ODA and SKO

Driver Elasticity

Driver elasticities determine the sensitivity of changes in energy-service demand to changes in the underlying driver. An elasticity of 1 means that a change of the underlying driver is exactly reflected in the energy-service demand. Energy-service demands with an elasticity below 1 are demand inelastic, while those with an elasticity of one or higher are demand elastic. In general it is assumed that energy-service demands grow slower than the underlying driver, such as GDP, GDP per capita or number of household. This decoupling of energy demand and economic growth is expected to increase during the 21st century so that all elasticities fall. Residential space heating (RH1), for example, has an elasticity of 0.8 in 2010, which drops to 0.5 in 2100. This means that initially the energy demand for space heating increases at 80% of household number growth, the specific underlying driver, and in the 2nd half of the century at only 50% of the household number growth rate.

Table 2-2: Driver elasticities for the United Kingdom

Energy-service demand	2010	2020	2030	2040	2050	2100
AGR	0.8	0.8	0.8	0.8	0.8	0.6
CC1	0.8	0.8	0.8	0.8	0.7	0.4
CCK	0.5	0.5	0.5	0.5	0.5	0.4
CH1	0.5	0.5	0.5	0.5	0.5	0.3
CHW	0.5	0.5	0.5	0.5	0.5	0.4
CLA	0.5	0.5	0.5	0.5	0.5	0.4
COE	0.5	0.5	0.5	0.5	0.5	0.4
COT	0.5	0.5	0.5	0.5	0.5	0.4
CRF	0.5	0.5	0.5	0.5	0.5	0.4
I00	0.6	0.6	0.6	0.6	0.6	0.5
ICH	0.8	0.8	0.8	0.8	0.7	0.5
IIS	0.7	0.7	0.7	0.7	0.7	0.5
ILP	0.8	0.8	0.8	0.8	0.7	0.5
INF	0.8	0.8	0.8	0.8	0.7	0.5
INM	0.8	0.8	0.8	0.8	0.7	0.5
IOI	0.8	0.8	0.8	0.8	0.8	0.6
NEO	0.6	0.6	0.6	0.6	0.6	0.5
NEU	1	1	1	1	0.9	0.5
ONO	0.6	0.6	0.6	0.6	0.6	0.5
RCD	1	1	1	1	1	0.8
RCW	1	1	1	1	1	0.8
RDW	1	1	1	1	1	0.8
REA	1	1	1	1	1	0.8
RH1	0.8	0.8	0.8	0.8	0.8	0.5
RK1	0.7	0.7	0.7	0.7	0.7	0.5
RL1	1	1	1	1	0.9	0.7
ROT	1	1	1	1	1	0.8
RRF	1	1	1	1	1	0.8
RHW	1	1	1	1	1	0.8
TAD	1.2	1.2	1.1	1.1	0.9	0.1
TAI	1.2	1.2	1.1	1.1	0.9	0.1
TRB	0.7	0.7	0.7	0.7	0.7	0.8
TRC	0.7	0.7	0.7	0.7	0.7	0.4
TRE	0.7	0.7	0.7	0.7	0.7	0.7
TRH	0.7	0.7	0.7	0.7	0.7	0.4
TRL	0.7	0.7	0.7	0.7	0.7	0.4
TRM	0.7	0.7	0.7	0.7	0.7	0.4
TRT	1.2	1.2	1.2	1.2	1	0.5
TRW	0.7	0.7	0.7	0.7	0.7	0.7
TTF	1	1	1	0.8	0.6	0.1

TTP	0.8	0.8	0.8	0.8	0.8	0.7
TWD	0.8	0.8	0.8	0.6	0.5	0.1
TWI	0.8	0.8	0.8	0.6	0.5	0.1

Non-energy demands are not explicitly considered.

Regional GDP per capita is a driver for the model, but there are no income distribution within a given region. Access issues are not considered either.

Regions can be split to additional subregions for the demand level, thus allowing to model demand separately for, for example, urban and rural areas in the Residential sector. Currently, USA and CAN have four and three geographic regions, respectively, while AFR, CHI, IND, MEA and MEX each have two ?sub-regions?, corresponding to rural and urban areas.

Behavioural change

Behaviour and heterogeneous agents are mostly not explicitly considered but are represented via price mechanisms e.g. there is no modal shift in the transport sector. With the exceptions of technology and region specific discount rates and price responsive energy service demands i.e. see Residential sector. Diffusion constraints can be implemented to simulate behavioural inertia (among the other barriers that are not explicitly included in the model).

4.5) Technological change in energy - TIAM-UCL

TIAM-UCL represents technological change through exogenously determined cost-reductions and efficiency improvements for the various different technologies available, although learning curves have also been used in specific studies. However, R&D expenditures are not explicitly considered.

Technology vintages are fully represented and explicit growth and decline constraints can be used to simulate the diffusion and phase out of technologies.

Representation of inertias and path-dependencies, e.g. via capacity stocks, knowledges stocks (cf. technological change), constraints of the expansion and decline of technology deployment, and early retirements of fossil capacities are all included.

Endogenous technological learning is also possible.

5) Land-use - TIAM-UCL

No land-use representation in TIAM -UCL except for land-use emissions from the agriculture sector.

6) Emissions - TIAM-UCL

In the sub-sections of this chapter, the GHG and non-GHG emissions included in TIAM-UCL are presented.

6.1) GHGs - TIAM-UCL

Carbon dioxide, Methane and Nitrous Oxide are all modelled in TIAM-UCL and these are linked to each individual technology.

TIAM includes energy related CO_2, land-use (and forestry) CO_2, and non-CO_2 gases CH_4 and N_2O. CH_4 from upstream, landfills, manure, rice paddies, enteric fermentation, wastewater is based on EMF-22 data and WEO-2008. N_2O from industry and agriculture is based on WEO-2008. CO_2 from land-use is based on the Reference scenario of the United States Climate Change Science Program (MIT) presented in Prinn et al. (2008). UK data for Non-CO_2 gases are taken from UK greenhouse gas inventory national system (www.ghgi.org.uk).

Some other greenhouse gases (CFCs, HFCs, SF_6, etc.) and chemically active gases such as NO_X, CO, VOCs are not explicitly modelled, but their radiative forcing is represented as an exogenous extra term in the Forcing expression (this is only for climate module). When aggregate non-CO_2 emissions (CH_4 and N_2O) to CO_2 equivalent, the model uses a factor of 0.025 for CH_4 and 0.298 for N_2O.

The emissions accounting for non-CO_2 emission sources are listed in Table 5.1 below. These emission sources are important to include when running climate targets taking account of all GHGs. Emission levels are exogenously determined using EMF data.

'*Table 5.1: Non-CO'*$_2$ **emission sources**

Sector	Emission source	GHG
Industry	Adipic Acid Production	N_2O
Industry	Nitric Acid Production	N_2O
Agriculture	Manure	CH_4
Agriculture	Other e.g. residue burning	CH_4
Agriculture	Other	N_2O
Residential	Landfill	CH_4
Residential	Other e.g. wastewater	CH_4

6.2) Pollutants and non-GHG forcing agents - TIAM-UCL

Pollutants and non-GHG forcing agents are not explicitly modelled, however additional forcing factor are included in the climate module.

7) Climate - TIAM-UCL

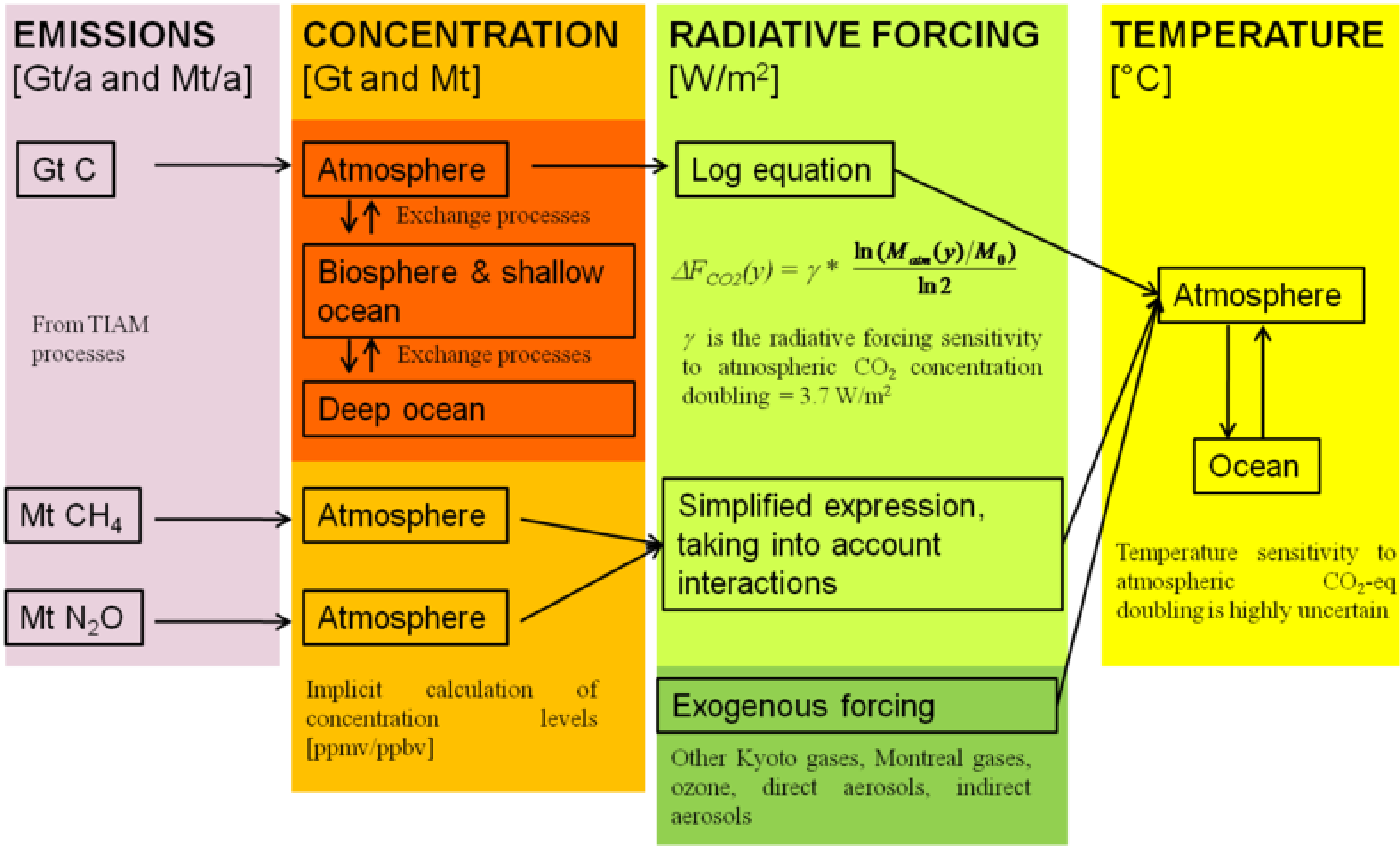
The climate module is a simplification of the climate system incorporating emissions of three major greenhouse gases (carbon dioxide, methane and nitrous oxide) to calculate radiative forcing and temperature changes. The results of the climate system (temperature change) can been linked to simplified damage functions to calculate future costs brought by climate change. We have extracted damage functions from the integrated assessment model PAGE09 (Hope 2011). After a recalibration of the climate module of TIAM-UCL (http://www.ucl.ac.uk/silva/energy-models/models/tiam-ucl) using the latest version of the MAGICC climate model (Meinshausen et al. 2011), we have matched data from the 8 regions within PAGE onto the 16 regions included within TIAM-UCL to produce the climate module

The climate module uses emissions that are endogenously calculated in TIAM as an input. These are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20). Successively, it calculates changes in the concentration of CO_2, CH_4 and N_2O, change in radiative forcing over pre-industrial times from all three gases plus an exogenously defined additional forcing and finally the temperature change over pre-industrial times for the atmosphere and the deep ocean. Figure 5.1 gives a graphical overview of the modules structure.

The underlying mathematical structure of the module is based on a linear recursive approach from Nordhaus and Boyer (1999). This is a well-documented, albeit simple approach, which gives a good approximation of more complex climate models (Loulou et al. 2010, p. 3).

Instead of converting non-CO_2 greenhouse gases into CO_2-equivalents and calculating concentrations and radiative forcing on this basis, the module models the life cycle of each endogenous emission separately.

Figure 5.1: Illustration of the TIAM climate module <figure id="fig:climate_module.png">



8) Non-climate sustainability dimension - TIAM-UCL

In TIAM-UCL, non-climate sustainability is not currently modelled.

9) Appendices - TIAM-UCL

10) References - TIAM-UCL

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